Influence of Digital Elevation Model Errors on the Reliability of Maps Depicting Earthquake-Triggered Landslide Hazards

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Key Words

Slope failures (includes landslides), geotechnical, earthquake effects

Investigations Undertaken

Elevation errors in a typical U.S. Geological Survey 10 m digital elevation model (DEM) covering an 18 km^2 portion of Seattle were estimated by comparing interpolated DEM elevations to1660 static and stop-and-go kinematic differential GPS measurements (Figure 1). The effects of the elevation errors on seismic slope stability calculations were then evaluated by using sequential Gaussian simulation with normal-score back transforms to produce 25 equally probable realizations of the elevation error distribution. Each of the error realizations was subtracted from the DEM to produce an alternative but equally probably version of the study area topography, and the topography realizations were used to calculate slope angle, static factor of safety, Newmark critical acceleration, and slope displacement maps. The effects of the DEM errors were quantified using a series of standard deviation maps that show the spatial distributions of uncertainties in each of the maps.

A secondary portion of the study, which was undertaken on a time-available basis towards the end of the project and is currently being completed, involved the use of high resolution (2 m) LiDAR DEMs from urban and suburban-rural parcels the Seattle area to estimate the additional component of slope angle error introduced by discrete sampling of a continuous topographic surface (sub-raster topography)

Results

Declustered elevation error data from the study area have a mean of –0.92 m, a standard deviation of ±2.36 m, and multi-scale spatial correlation that extends over distances ranging from tens of meters to kilometers (Figures 2 and 3). These results are comparable to the errors measured by Fisher (1998) and Holmes and others (2000) using DEMs produced by both the U.S. Geological Survey and the British Ordnance Survey;

therefore, it appears that an elevation error standard deviation on the order of ±2 m is not unusual for an off-the-shelf DEM. Weak correlations between error and both elevation and slope angle (r^2 of 0.07 and 0.12, respectively) were ignored in subsequent modeling because they each accounted for only a small portion of the elevation error variability.

Once the elevation errors were measured, sequential Gaussian simulation and normal score back-transformation (Goovaerts, 1997) was used to create 25 error realizations with the same statistical distribution and spatial correlation as the measured errors. Five such realizations are shown in Figure 4. The error realizations were subsequently used to create elevation, slope angle, static factor of safety, Newmark acceleration, and displacement realizations. Slope angles were calculated using a standard finite difference operator, the static factor of safety was estimated using typical geotechnical properties for Seattle area deposits (McCalpin, 1997), the critical acceleration beyond which slope movement occurs was calculated using the standard Newmark (1965) relationship, and total slope displacement was calculated as a function of Newmark acceleration and Arias intensity using the regression equation developed by Jibson and others (2000). These results are conveyed in maps showing the distribution of mean values and standard deviations for each of the mapped quantities (Figure 5).

The maximum slope angle uncertainty magnitude decreases from more than 10° to about 4° as slope angle increases, but that the minimum slope angle uncertainty varies between ±1° and ±2° regardless of slope angle. Combined with the results of previous studies such as Fisher (1998) and Holmes and others (2000), the results of this study suggest that slope angles calculated from standard 10 m or 30 m U.S. Geological Survey DEMs should be assumed to have standard deviations of at least ±2° to ±5°. The effects of these slope angle errors should be factored into any calculations making use of DEM-derived slope angles.

The resulting uncertainties in calculated Newmark displacements for a hypothetical earthquake with an Arias intensity of 4 m/s affecting the study area are in most cases less than ±3 cm, but some values are greater than ±10 cm. One way to predict areas susceptible to earthquake-triggered landsliding is to compare the calculated mean displacement for each DEM grid point or raster to a threshold, for example 10 cm of displacement. When this is done for the study area, 0.55% of the area is predicted to be susceptible. Uncertainty in slope angles, however, means that there is a considerable probability that the true displacement is greater than the calculated mean and the maximum probability of misclassifying a susceptible grid point as stable is 50%. Another way is to compare the threshold displacement with the displacement that has a 5% or less probability of being exceeded for each grid point (in other words, a 95% certainty criterion). When this more conservative approach is taken in order to account for uncertainties arising from DEM errors, 4.1% of the study area is predicted to be susceptible. In this case, therefore, ignoring slope angle errors that arise from DEM errors under-predicts the area susceptible to earthquake triggered landsliding by a factor of 7.5.

Multi-scale resampling of 2 m LiDAR DEMs for one rural-suburban area and one urban area in the Seattle region shows that sub-raster topography typically adds an additional ±1° to ±3° of uncertainty to slope angles calculated from off-the-shelf U.S. Geological Survey DEMs.

Non-Technical Summary

Global positioning system (GPS) surveying and computer simulations of Earth's surface showed that errors in a U.S. Geological Survey digital elevation model (DEM) covering a portion of Seattle, Washington, introduce errors into the calculations used to produce maps of earthquake-triggered landslide susceptibility. Elevation errors give rise to slope angle errors, which in turn give rise to significant errors in seismic slope stability calculations. The results of this study suggest that unless the effects of elevation errors are taken into account, landslide susceptibility maps based on standard U.S. Geological Survey DEMs are of questionable reliability and may seriously underestimate landslide hazards.

Reports Published

Haneberg, W.C., 2004, Effects of digital elevation model errors on slope angle, static factor of safety, and Newmark acceleration uncertainty in GIS-style landslide hazard modeling: Geological Society of America *Abstracts with Programs*, Vol. 36, No. 5, p. 297.

Haneberg, W.C., submitted, Effects of digital elevation model errors on spatially distributed seismic slope stability calculations: an example from Seattle, Washington: *Environmental & Engineering Geoscience*.

Haneberg, W.C., in preparation, Multi-scale resampling of LiDAR DEMs to estimate the influence of sub-raster topography on slope angle errors: for submission to *Geomorphology*.

In addition to the abstract and papers listed above, hour-long oral presentations describing the research were given at the University of Cincinnati, Western Washington University, and the Washington Section of the Association of Engineering Geologists.

Data Availability

The GPS data collected this project are available as a tab-delimited text file from the PI (William C. Haneberg, Haneberg Geoscience, 10208 39th Avenue SW, Seattle WA 98146, bill@haneberg.com, 206 935-0846) and will also be provided as a tabular appendix to the project final report.

References Cited

Cressie, N. and Hawkins, D.M., 1980, Robust estimation of the variogram: *Mathematical Geology*, v. 12, p. 115-125.

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Holmes, K.W., Chadwick, O.A., and Kyriakidis, P.C., 2000, Error in a USGS 30-meter digital elevation model and its impact on terrain modeling: *Journal of Hydrology*, v. 233, p. 154-173.

Jibson, R.W., Harp, E.L., and Michael, J.A., 2000, A method for producing digital probabilistic seismic landslide hazard maps: *Engineering Geology*, v. 58, p. 271-289.

McCalpin, J.P., 1997, *An Improved Procedure for Mapping Earthquake-Induced Landslide Potential Using a Geographic Information System, With Applications to the Puget Sound Region*: Geo-Haz Consulting, NEHRP Final Technical Report, Contract 11434-95-G-2550, 53 p.

Newmark, N.M., 1965, Effects of earthquakes on dams and embankments: *Geotechnique*, v. 15, p. 139-160.

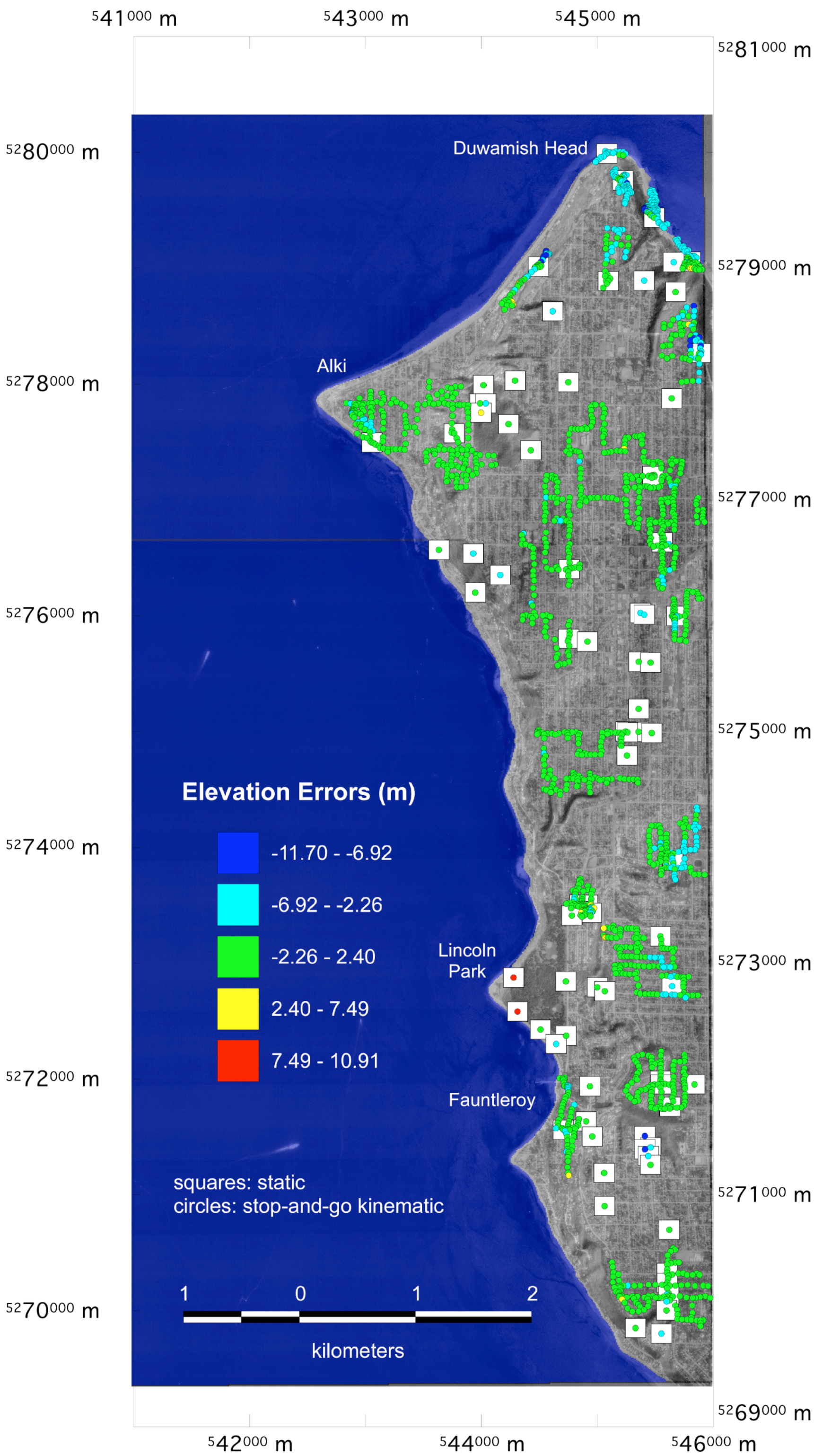

Figure 1. Map of study area, covering part of the Duwamish Head 7.5' quadrangle and showing location of GPS measurements and elevation errors. Many of the stop-and-go kinematic data points are not visible because of their close spacing. Coordinates are UTM zone 10N referenced to the NAD83 geodetic datum.

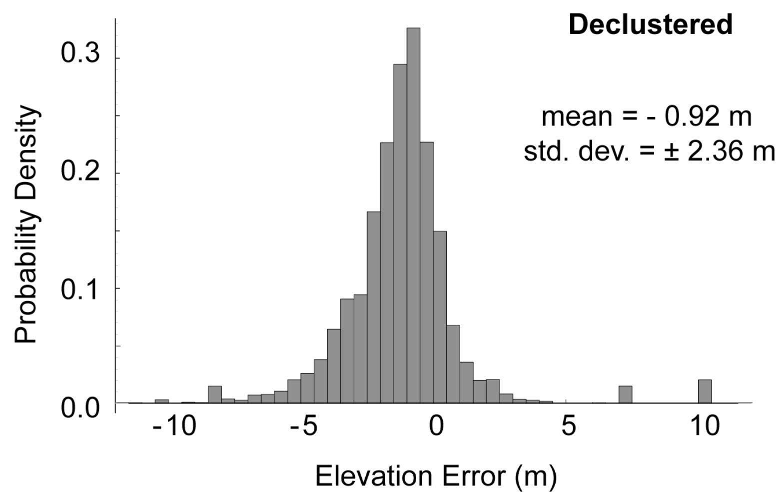

Figure 2. Histogram showing the distribution of 1660 elevation errors measured in the study area. A cell-declustering process was used to account for the effects of non-uniform sample distribution across the study area.

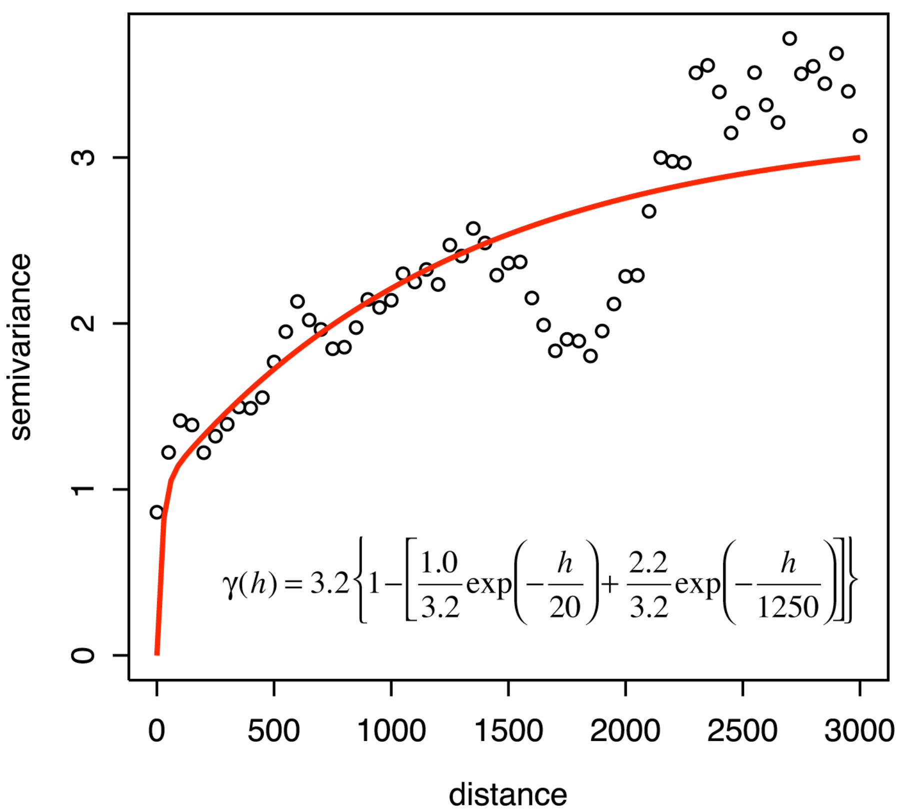

Figure 3. Empirical (circles) and modeled (red line) variograms for the elevation error data. The empirical variogram was calculated using the Cressie and Hawkins (1980) robust method. $\gamma(h)$ is the modeled semi-variance (m^2) and h is the lag (m).

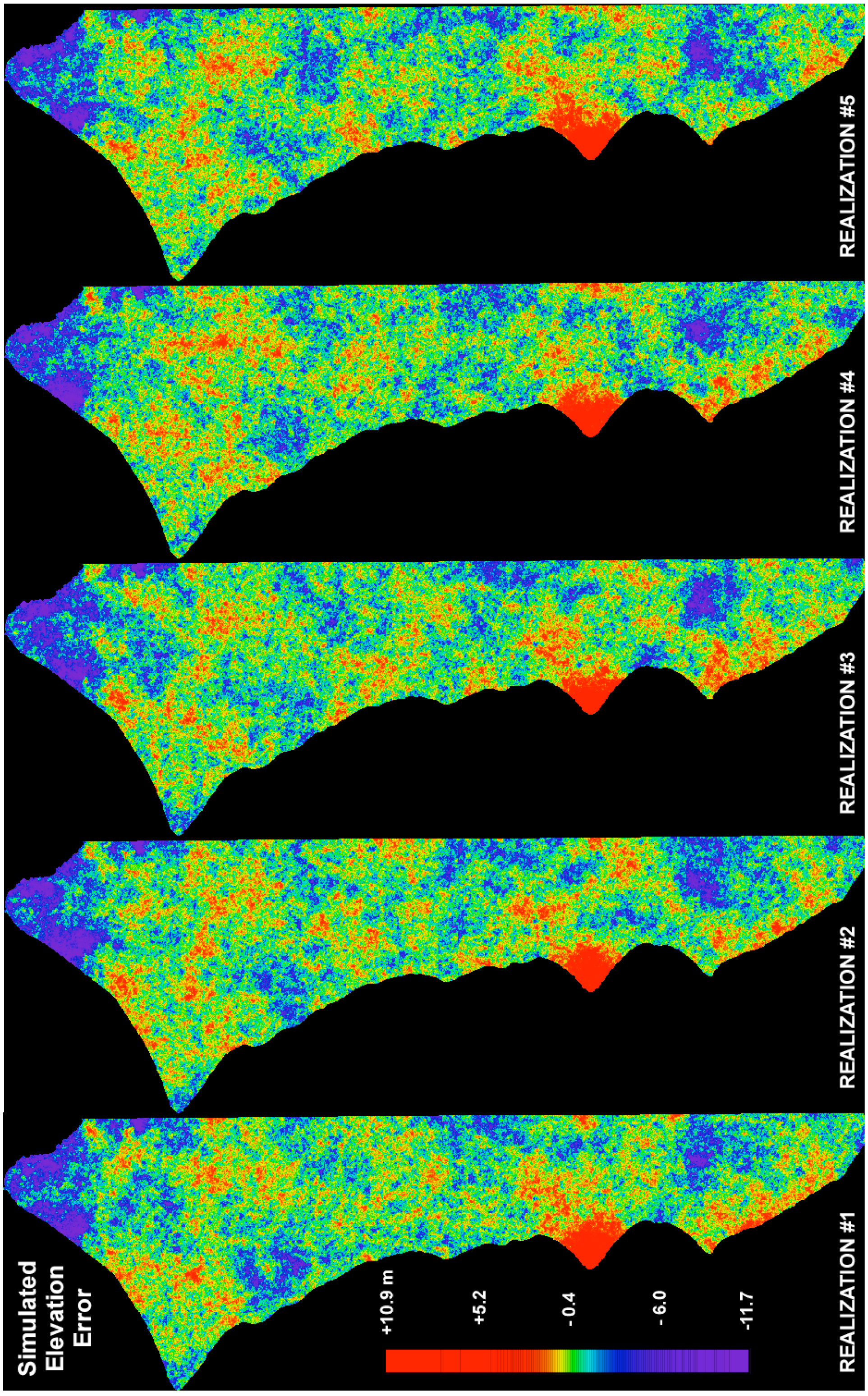

Figure 4. Five of the 25 elevation error realizations generated using sequential Gaussian simulation with normal score back transformation. Each realization contains 182,700 values on a 10 m grid and the same statistical distribution of errors that was estimated using centimeter-accurate differential GPS surveying in the study area.

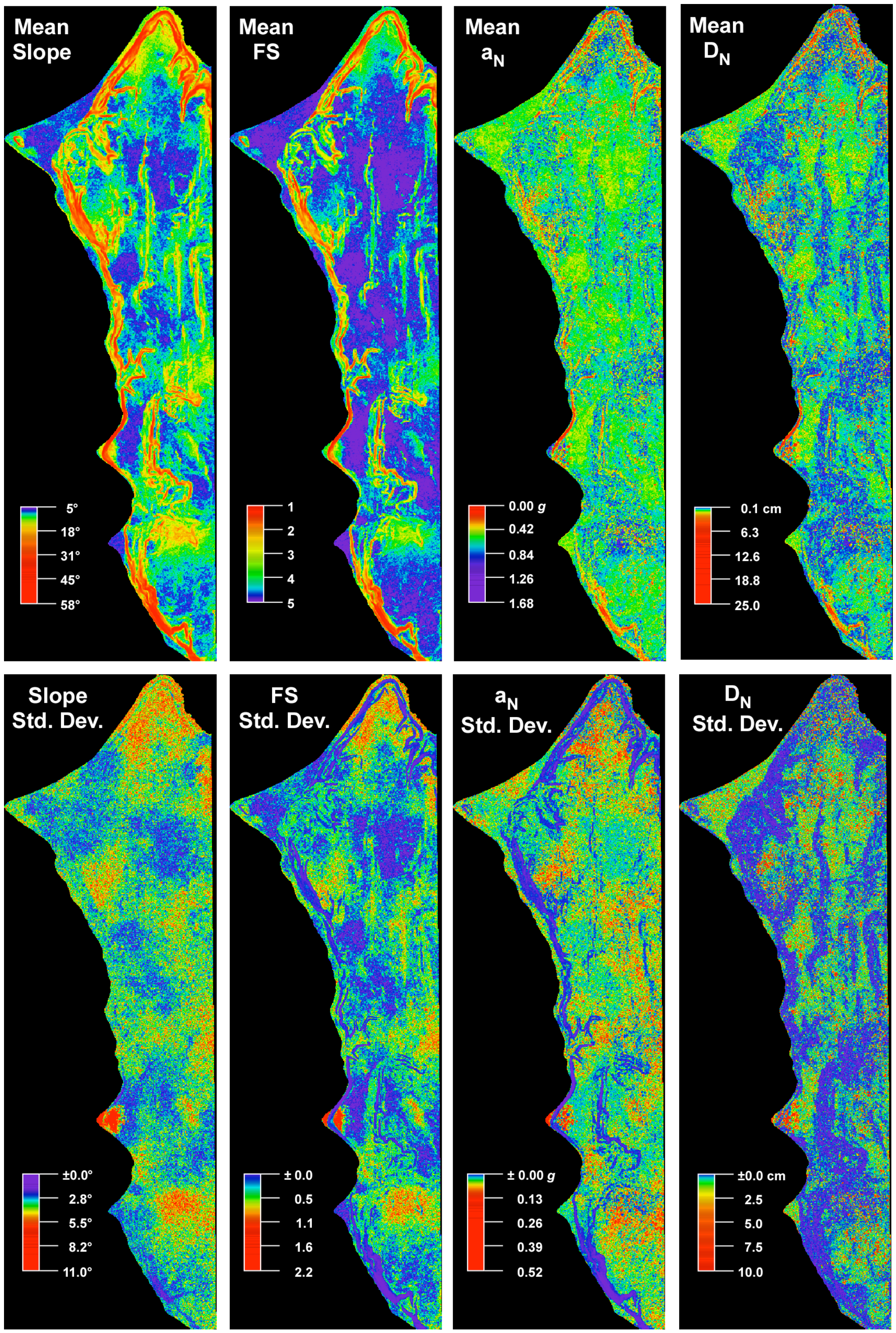

Figure 5. Maps showing the spatial distribution of mean values and standard deviations for variables used in seismic slope stability calculations, based on 25 stochastic error realizations of the type shown in Figure 4. *FS* is the static factor of safety for typical Seattle surficial deposits, a_N is the Newmark (1965) critical acceleration, and D_N is the displacement calculated using the Jibson and others (2000) regression equation for an Arias intensity I_A = 4 m/s earthquake.